DISCLAIMER: This document was originally written as a *final design report*. It is rather complete, both long and detailed. It's more than a typical student might be expected to generate. The topic is not the same as your topic. There are fewer sections but more detail. Adjust your report as needed.

Technical-Report: A Holiday-Light Timer

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For each section, list the primary author by netID followed by contributing authors in decreasing order of contribution. Do not list teammates who had little-to-no contribution to a section.

Abstract (cdschmit)

Writing a college technical report may vary by department and by class and even between midterm and final reports. Many students will be inclined to submit sub-par work that merely reproduces earlier data without tying the concepts together into a coherent report. Our goal here is to provide a structure and some insight into writing a strong technical report. While the content and number of sections will differ from the report(s) you are to generate, the topics outlined in the rubric are well addressed.

Introduction/Overview (cdschmit, netid2, netid3)

Battery-powered holiday lights are great! They are small and lightweight and, due to the use of power-efficient LED bulbs (thanks, Prof. Holonyak!), the batteries last for quite a while. But then, again, you do have to remember to turn them off! In this project, we am taking a strand of "fairy lights" (similar to https://www.amazon.com/gp/product/B07WG18RLT?pf_rd_r=NCN1T4HV65957BM4ESX5&pf_rd_p=edaba0ee-c2fe-4124-9f5d-b31d6b1bfbee, with an *assumed* schematic shown in Figure 1), and modifying them to include a timer circuit based on an RC time constant. An RC time constant means that there is a resistor of value R and a capacitor of value C where the time constant $\tau = RC$ can be adjusted to control the time it takes to charge and/or discharge the capacitor (reference: ECE 110 Lab https://courses.engr.illinois.edu/ece110/fa2021/content/labs/Experiments/C_RC_TimeConstant_Falstad_v2.pdf, flow chart in Figure 2).

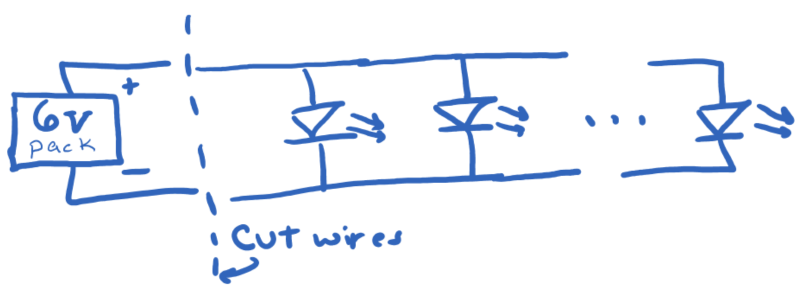

Figure 1: The fairy lights and where we plan to cut them.

Figure 2: A flow diagram of what we want to happen.

Before we start this project, we should take a look at the rubric to make sure we have in mind everything that our teachers recognize as valuable in technical project report (for the midterm report: https://courses.engr.illinois.edu/ece110/fa2021/content/labs/archive/Skill_HCD_WrittenReport.pdf). We see emphasis of the midterm report should be on Format (looks professional), Communication (concepts are intelligible), Tools (proper tools lead us to trust the content), Teamwork (while individuals did the work, the total is greater than the sum of the individuals), and Conclusions (why was this effort undertaken at all?). [Instructor note: The final project should not lack on any of these, but also include an emphasis on Design (including considerations from data sheets and using our technical training to make informed decisions, show ***creativity***), Troubleshooting and Validation (including making predictions based on theory and validating them using the physical build and our lab tools like the oscilloscope), Communication (which is our ability to relay our design and our technical understanding; making ***connections*** to the course material for the instructors and anyone else who might want to learn from our report), Conclusions and Future (which provide us the opportunity to plan for improvements that time or resources may not currently allow), as well as our overall presentation (also related to communication, but we want this report to have a professional feel…clear structure, figures, language, etc.).] Someone should pick up our report and feel like they have something of ***value*** in their hands!

Design (cdschmit, netid2)

In our case, we had the opportunity to start from scratch with an idea. To get our fairy lights to turn on and off automatically, we thought of using the nMOS as a switch. From ECE 110, we have only learned how to use the nMOS when setting the source to the negative end of the battery, so we'll be cautious and stay with that configuration so that we understand the IV characteristics. We can replace R_D in that traditional configuration with the LED strand and a current-limiting resistor, R_{CL}. The voltage source $V_{DD} = 6\ V$ will be the battery voltage (the fairy lights use two CR2032 3-volt batteries). See Figure 3. Now, we need to decide how to implement the RC time constant.

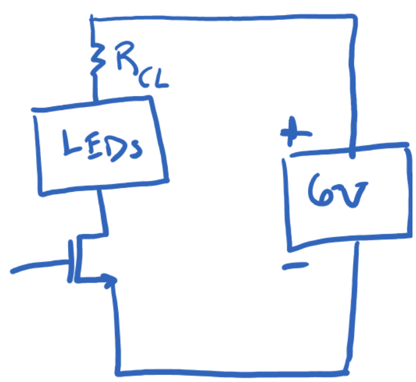

Figure 3: Adding a current-limiting resistor and an nMOS switch.

we know we need to maintain a voltage at the gate pin of the nMOS to keep it turned on for a while. We'll use a capacitor there. To charge the capacitor quickly, we can use a pushbutton from our kit. The pushbutton can momentarily connect the top of the capacitor to the battery supply for a quick charge. Since I'm not using a resistor in this connection, we can expect the capacitor to charge very quickly to the battery voltage ($t_{rise} \approx 2.2\ RC = 2.2 \times 0 \times C = 0\ s$). The button serves to turn on the light strand (Figure 4).

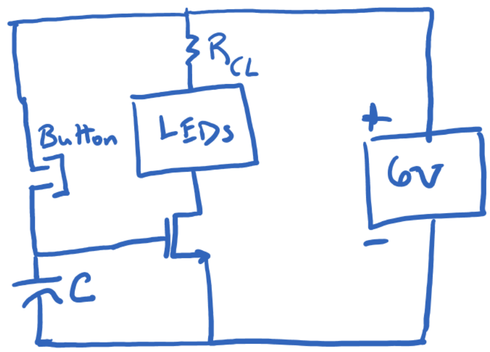

Figure 4: Adding a capacitor to control the gate voltage and button to fast-charge it.

A quick check of the **datasheet** for the MOSFET (https://cdn.sparkfun.com/datasheets/Components/General/FQP30N06L.pdf) reveals that the maximum gate voltage is 20 volts. We are operating at 6 volts, safely below that limit.

For the lights to turn off automatically, we can add a resistor in parallel with the capacitor so that once we release the turn-on button, the capacitor will start to discharge through the resistor (Figure 5). We'll want the resistor large enough so that the capacitor does not discharge too fast. What values should we use for C and R? The largest capacitor in our kit is $1000\ \mu F$, so we'll start with that. If we want our timer to run for about 30 minutes, we can work backwards to choose the resistor value.

$$t_{fall} = 30\,\mathrm{min}\left(\frac{60\ s}{1\ min}\right) = 1800\ s$$
$$\tau = \frac{t_{fall}}{2.2} = 818\ s = RC = R \times 1000\ \mu$$
$$R = \frac{818}{1000\ \mu} = 0.818\ M\Omega$$

Here, t_{fall} is the time expected for the capacitor to drop from 90% to 10% of the battery voltage. Looking at our kit contents (https://courses.engr.illinois.edu/ece110/content/labs/KitContents/ECE110_kit_components.xlsx), we see that we have a $1\ M\Omega$ resistor that should work nicely in providing us with a timer circuit on the order of 30 minutes. Recalculating:

$$t_{fall} = 2.2 \times (1\ M \times 1000\ \mu) = 2200\ s = 36.7\ min$$

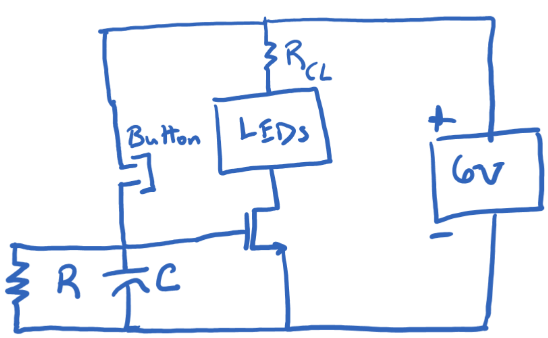

Figure 5: The resistor R provides a discharge path for the capacitor and completes the RC time constant.

we got lucky. The largest capacitor and the largest resistor in our kit provided just a perfect time constant for me. If we wanted the timer to last, say, an hour, we could use two $1\ M\Omega$ resistors in series.

Should we add a shut-off switch as well? We could add a second button that allows us to short out the resistor and discharge the capacitor instantaneously. This would be safe as long as no one presses both buttons at the same time (shorting the battery to ground). But then, there is also a shut-off on the battery pack itself. We think it is better to not provide this feature.

Power efficiency should also be a concern. If our goal is to save battery life through a timer circuit, we should also consider how much energy is expended by the timer circuit itself. We should start thinking about where power might be wasted (not appearing as light output). The current-limiting resistor stands out to me. There didn't seem to be one in the original circuit. Why not? We cut the wires on our fairy lights. We measured the open circuit voltage of the 6-volt battery pack to be 6.17 volts. Then, when driving the LEDs, it fell to 2.57 volts. Ahhhh, the battery pack is not ideal. We might model it as a Thevenin circuit with an internal resistance that is high enough to current-limit and protect the LEDs without adding an external current-limiting resistor (Figure 6).

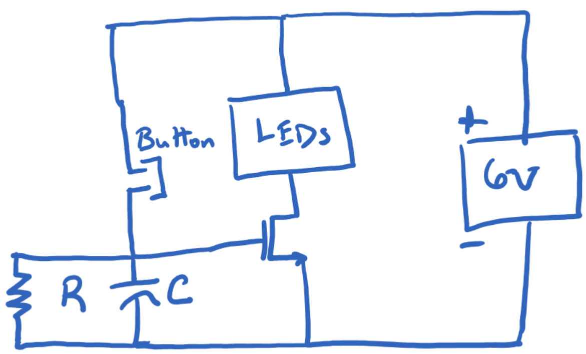

Figure 6: If the original 6-volts drove the LEDs directly, do we need the current-limiting resistor?

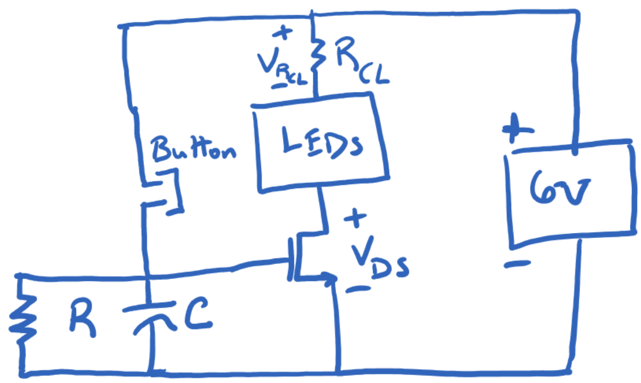

Figure 7: The current-limiting resistor can still be useful for measurements!

When the lights are on, how much power is consumed by the timer circuit? Hopefully, it will be a fraction of the power consumed by the lights so that the power efficiency remains high. The energy consumed by the charging of the capacitor is merely

$$E = \frac{1}{2}CV^2 = \frac{1}{2}(1000\mu)(6^2) = 18000\ \mu J$$

This is a one-shot energy usage that we might average over the approximately 37 minutes of timer usage giving us an effective power wasted in charging the capacitor of

$$P = \frac{18000\ \mu}{2200} = 8.18\ \mu W$$

The power consumed by the transistor's drain-to-source connection will be the current through the light strand times the voltage across the drain-to-source nodes. Neither of these values are likely to be constant as the capacitor discharges, but we might expect the worst-case power dissipation near the beginning or, perhaps, near the end of the timer circuit's activity (as these are the extreme events)…or just as the lights dim out. These will be difficult to estimate using the datasheet of the MOSFET (too much variance in the parameters), so we'll just rely on measurements from our circuit build.

Troubleshooting and Validation (cdschmit, netid3, netid2)

We are now ready to build. The build will be sequential as we don't want to throw everything together and just pray it works. We want to have an *engineering* process. Each individual portion can be constructed and tested so that we have confidence in the process and can make repairs as needed when the circuit is simple enough to repair quickly. We'll create a plan.

Step 1: Cut the fairy lights away from the battery and understand the battery as well as the LED configuration.

Step 2: Add the nMOS with gate set "high" and make sure they turn on.

Step 3: Add the capacitor and charge button to make sure we can turn LEDs on this way.

Step 4: Add a much smaller resistor to set the time constant low and make sure the timing circuit is functional. This should be easy to see with the oscilloscope if watching the voltage across the capacitor.

Step 5: Replace the small resistor with the $1\ M\Omega$ value, charge the cap with the button, and wait 30 minutes to see if they go off! The oscilloscope is still useful, but this voltage should change very slowly.

Step 1:

As mentioned before, we found an open-circuit operating point for the battery to be $(6.17\ V, 0\ mA)$. With the lights attached and using $R_{CL} = 100\ \Omega$, we measured $V_{bat} = 3.29\ V$ and $V_{R_{CL}} = 0.602\ V$ which, through Ohm's Law gives $I = \frac{0.602\ V}{0.1\ k\Omega} = 6\ mA$. Doing a direct fit to these two operating points of the ***battery*** (Figure 8) provide a quick model for the internal resistance of $R_T = \frac{\Delta V}{\Delta I} = 478\ \Omega$. No wonder the fairy lights don't need a current-limiting resistor! We also measured $V_{LEDs} = 2.66\ V$. The voltage across the LEDs seems consistent with datasheets on LEDs (for example, the red LED at http://www.rmrco.com/prod/rosr/parts/04.12.16.02_Components/04.12.16.09_led_red.pdf), so we feel confident they are really arranged in parallel as assumed in Figure 1.

Vop	Iop
6.17	0
3.29	6.02

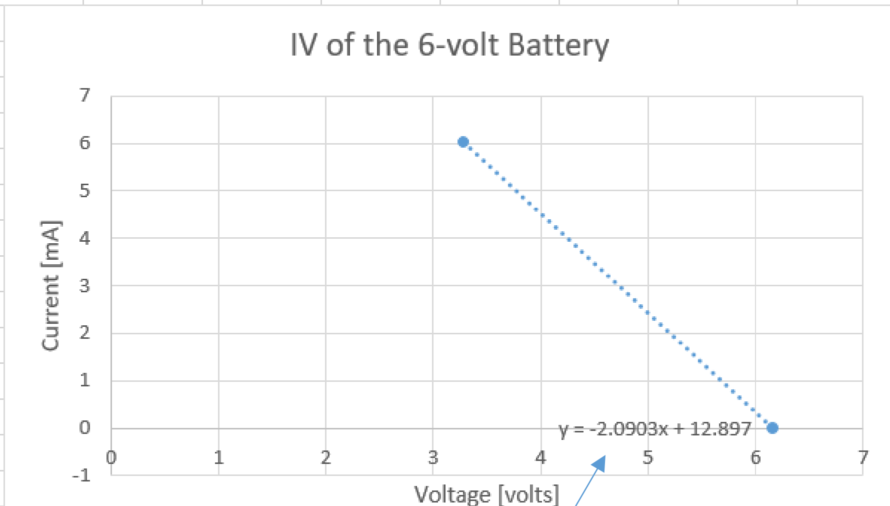

Figure 8: Using Excel to plot the IV of the battery and curve-fit to find the effective resistance, R_T.

Step 2:

In step 2, we built the circuit of Figure 3 and attached the gate pin of the nMOS to the positive terminal of the battery. We did this both with $R_{CL} = 100\ \Omega$ and then again with it removed. The LED strand lit up in both cases. While it was a bit brighter without the resistor, there was also no damage incurred. We are glad we did step 1!

You can resize images, but as a rule don't shrink the font to less than "9-pt font" or it will be difficult to read!

Step 3:

we built Figure 4 on the breadboard. The press of the button caused the LED lights to come on instantly. We were curious if the capacitor charged to the open circuit voltage of the battery or did it charge to the operating voltage of the battery when the lights are on? To find out, we attached the oscilloscope (see video) across the capacitor and watched the voltage as the button was pressed. The capacitor voltage went only to 2.70 volts, therefore confirming that the battery voltage drops very quickly from open-circuit to the operating voltage as the lights come on. Gate voltage will not be the open-circuit voltage.

Step 4:

We completed the circuit of Figure 6 but used $R = 1\ k\Omega$ so that the time constant would be 100 times less than the original design. That would mean the cap should discharge in about 0.037 minutes or a couple seconds. Indeed, pressing the button caused the lights to come on and "extinguish" in a second or two as expected. It was faster than we wanted, so we replaced it with a $10\ k\Omega$ resistor. The results were satisfying as we could watch the oscilloscope (see video) show the capacitor charge instantly and then discharge over the course of 8-10 seconds as the lights eventually went out.

Step 5:

We are now ready! Inserting $R = 1\ M\Omega$, we pressed the button to start the glorious LED light! While I'm tempted to set a timer and come back in about 30 minutes to check on it, I'm too excited! We grab a book and drape the lights across our table. The time is 9:07pm. By 9:25pm, the lights have significantly dimmed, but have not turned off. We were hoping for something more sudden, but as the gate voltage falls, the operating point will move into the "Ohmic" portion of the IV curve and the current will continue to fade gradually and not shut off suddenly. The reason we are off on our time constant is because we were originally assuming the threshold voltage of the nMOS, V_{TH}, would be near zero and much less than the battery voltage (and the starting capacitor voltage). Returning to the datasheet for the nMOS, on page 2, it is revealed that $V_{TH} = V_{GS(th)} = 1\ to\ 2.5\ V$. This range makes the potential threshold voltage very close to the non-ideal operating voltage of the battery (the starting voltage of the capacitor) and is likely to both reduce the effective fall time of the circuit and reduce efficiency as the percentage time the LEDs live in transition to shutoff is increased as well. In practice, we watched the gate voltage and noticed the LEDs were notably dimming at $V_{GS} = 1.75\ V$ and essentially off by $V_{GS} = 1.5\ V$. T_{fall} is optimistic. To further test our theory, we inserted a $1\ k\Omega$ current-limiting resistor and used a 9-volt battery and the circuit ran very close to the original design including just over 30 minutes of timed operation!

Returning to power efficiency, we realized that the voltage $V_{CE} \approx 0\ V$ until the LEDs have gone dark. It is at this point that the current gradually goes to 0 while V_{CE} climbs towards 3.44 volts and (waste) power is consumed by the transistor. We don't think it is significant given the small amount of time in which this happens, but we haven't completed the analysis yet. The useful power can be estimated by $P_{useful} = V_{LED} \times I_{LED} \approx 2.57 \times 6.02\ m = 15.5\ mW$. This towers over the energy-converted-to-power used to charge the capacitor ($8\ \mu W$) and, considering the short amount of time for the final decay of the gate voltage, should be a couple orders of magnitude greater than the waste power of the MOSFET during the final stage of LED shut-down.

Conclusions and Future (cdschmit, netid2, netid3, netid4)

The circuit design worked very well. We were able to make predictions based on circuit theories and to validate those predictions using measurements on our prototype. We witnessed unexpected behavior but was able to use our circuit knowledge to understand the issues. Specifically, we were able to

- Design using circuit techniques learned in ECE 110 including RC time constants, nMOS as a switch, MOSFET regions of operation, and current-limiting resistance.
- Analysis using circuit techniques learned in ECE 110 including Ohm's Law, Thevenin-equivalent circuits, circuit modelling, and power efficiency.
- Use test-and-measurement equipment like a voltmeter and oscilloscope to measure and validate operation allowing us to both debug and display for the needs of our audience.

We ran short on time and did not complete a detailed power-efficiency analysis ($\eta \approx ?$). That will be a need for our future work, but we are happy to have at least started the process. We would also like to find a way to increase the starting voltage on the capacitor, perhaps by preventing the LEDs from lighting until after the capacitor has been charged. That would bring our time constant closer to the original design.

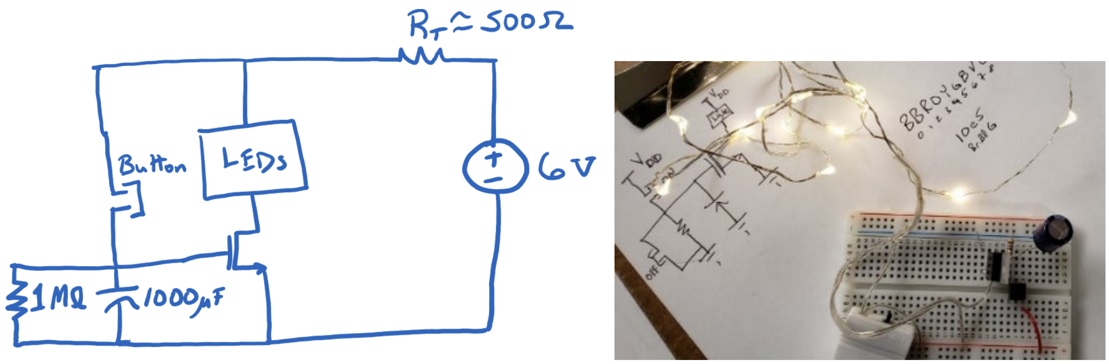

Figure 9: The circuit we designed and built including the model developed for the 6-volt battery source.

Future plans are to solder this onto a proto-board and to attach them to a personal hand-made gift, an illuminated advent calendar. We are happy with the current design in both its simplicity and power efficiency but might replace the original 6-volt battery with a 9-volt battery (or 6-volt AA pack), use $R_{CL} = 1\ k\Omega$, and add a shut-off button. We strongly recommend a time-constant project to others in ECE 110.

Christopher D. Schmitz (cdschmit): Sign here. ______________________

Teammate 2 (netid2): ______________________

Teammate 3 (netid2): ______________________

Teammate 4 (netid2): ______________________

Although we didn't specifically request signatures in the midterm report for Fall 2021, having each teammate attest to the originality of their contribution would help protect you from allegations of plagiarism.